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Implementation of Wind Power in the Dutch Power System

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Abstract—**We present the current status of wind power in the Netherlands and its future prospects, in particular for the development of offshore wind. An overview is given of the performance of the wind power on land. We briefly discuss the experience with OWEZ, the first offshore wind park commissioned April 2007, and the expectations for Q7, to be completed March 2008. The organization of the energy and imbalance markets in the Netherlands is described. Balancing requirements due to variability and limited predictability of wind energy are estimated, at system and market participant level. Next, we present the results of a wind power integration study performed in order to estimate the amount of wind curtailment due to the technical limitations of the conventional units in the Netherlands. It is found that due to must-run constraints on the combined heat and power units, which constitute over 50% of the Dutch production park, sufficient reserve is available to cover wind fluctuations and prediction errors for up to 8000 MW installed wind power. The only limiting factor is the minimum output of the conventional units, which may result in increasing curtailed wind starting around 4000 MW installed capacity. Changes in system operating costs, curtailed wind and total emissions due to the application of various large-scale storage technologies are described in the final section of the paper.**

I. Introduction

THE share of wind power in the European electricity supply has increased significantly in the past decade. With the recently set ambitious European targets for future increase in energy produced from renewable sources, the growth of wind power can be foreseen to continue. The development of wind power towards an energy source of significance will have substantial impacts on the operation of power systems. The variability and limited predictability of wind can cause power fluctuations in the system that are more difficult to manage than load variations or load forecasting errors. In particular, wind power influences the need for regulating power and calls for reserves in the minute to hour time frames [1]. These services are often provided by conventional (coal and gas-fired) generating units. Therefore, wind power must be taken into account in the commitment and dispatch of the other units in the system and, consequently, will have an influence on the technical and economical aspects related to the operation of these generators.

It is suggested that wind power and energy storage form a natural combination, for example in [2], [3], [4]. Wind power is used to fill up storage reservoirs during high wind periods and the stored energy may be used for electricity generation during calms. However, large-scale wind power will become part of the existing power system and its associated market structure. Therefore, the technical capabilities of the existing system will determine the constraints for integrating wind power. The technical and economic benefits of energy storage facilities for wind power should be considered for the whole system where both wind power and energy storage are integrated into. A system approach furthermore opens up a wider range of possible solutions for wind power integration.

In case a significant part of generation capacity is heat-demand constrained, such as the case in the Danish [5] and Dutch [6] power systems, due to a large percentage of combined heat and power (CHP) units, wind power may have to be curtailed at moments of low load and high wind. The flexibility of CHP-dominated systems to integrate wind power could be significantly increased by a more price-based operation philosophy for these units, according to [5]. A system-oriented approach is applied in [7] to investigate the net benefits of wind power under different generation portfolios. Reference [8] assesses the benefits of compressed air energy storage (CAES) in a case study for Germany using a stochastic electricity market model. It is found that the benefits of CAES are partly, but not solely, driven by the installed wind power.

In the Netherlands, 1.75 GW of wind power has been installed up to date (Jan. 2008), including 127 MW offshore wind. Governmental targets for the moment are 3.5 −4.0 GW onshore and 700 MW offshore capacity installed in 2011 and possibly 6–10 GW offshore by 2020. No large-scale energy storage facilities are currently available in the Netherlands, mainly due to the absence of geographically favorable locations in this flat country. The large share of heat-driven CHP units developed in the last decades, in addition to increasing distributed generation (DG) unavailable for dispatch challenge the integration of wind power [6].

This paper is organized as follows. First, an overview of the current implementation status of wind power in the Netherlands is given (Section II). Next, the structure of the Dutch liberalized electricity markets is briefly presented in section III. Balancing requirements due to the variability and limited predictability of wind at the

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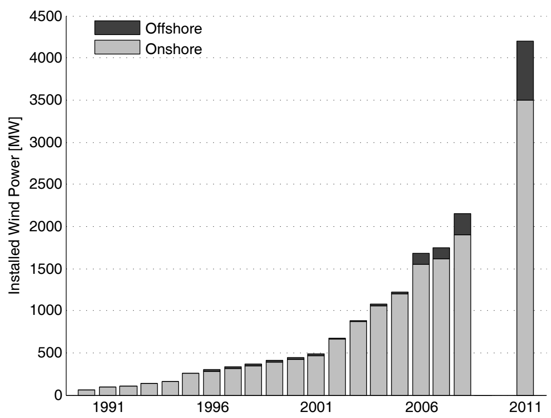

Figure 1. Installed and targeted wind power in the Netherlands.

central and market participant level are estimated in the next section. Then, results of integration studies performed by Delft University of Technology in cooperation with the Dutch TSO TenneT are presented in sections V and VI. Overall conclusions are presented in Section VII.

II. Current Status of Wind Power in the Netherlands

Originally, the government target for onshore wind power was 1000 MW installed by 2000. This capacity was reached in 2004, as can be seen in Fig. 1. A subsequent national target of a minimum 1500 MW onshore by 2010 was already reached by the end of 2006. As per end of 2007, installed capacity equals 1620 MW onshore and 127 MW offshore.

Following the ratification of the Kyoto protocol and the embracing of European Union targets for electricity production from renewable sources, national targets for 2011 currently include 3500–4000 MW onshore and 700 MW offshore wind power installed. The past few years were characterized by drastic changes in governmental policy and accompanying subsidy schemes. Especially the target for offshore wind in 2020 was a subject of political discussion. Nevertheless this period witnessed an upsurge of activities such as requests for environmental permits from developers to realize between 10 to 13 GW installed offshore wind power, equivalent to 27-32% of the present electricity consumption in the Netherlands. In addition, several studies on the issue of integration of large amounts of wind power in the Dutch electrical power system were commissioned.

The first offshore wind farm at Egmond aan Zee (OWEZ) was brought in operation in December 2006. This is a government-sponsored demonstration project, hence allowed within the Dutch offshore 12-mile zone. It is owned and operated by a joint venture of Shell Renewables and NUON, one of the major energy producers in the Netherlands. The installed power is 108 MW, consisting of 36 Vestas V-90 turbines of 3 MW each, placed at a distances 8–12 km from the coast. Due to its "near-shore" location, a submarine cable of medium voltage was deemed to be the most efficient solution, with a coastal substation that steps up the voltage to 150 kV.

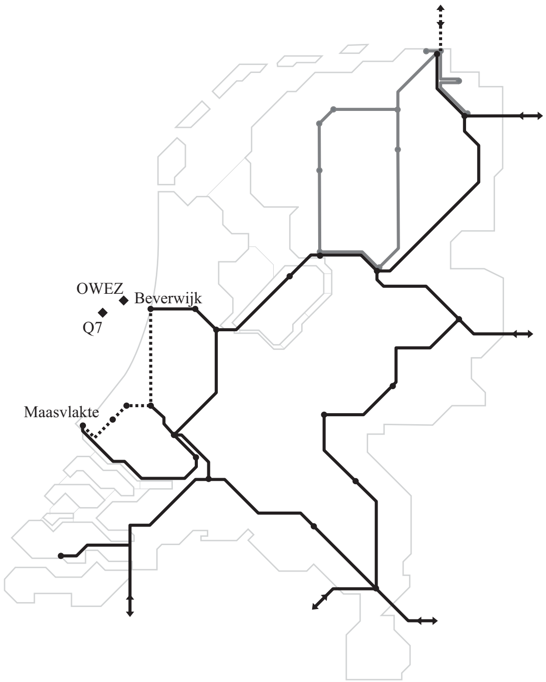

Figure 2. Offshore wind farms and EHV (380 and 220 kV) grid in the Netherlands, including planned reinforcements in the West.

Next, wind farm Q7 – expected completion date March 2008 – is the first truly commercial offshore wind park, developed through a tailor-made non-recourse financing scheme. The project was initially developed by E-Connection and later taken over by a group of companies including Econcern, ENECO and Energy Investment Holdings. The farm has an installed capacity of 120 MW, consisting of 60 Vestas V-80 turbines of 2 MW each – a more conservative choice of proven technology compared to OWEZ. Due to its location about 23 km from the coast, an offshore transformer substation has been built to step the voltage from the 22 kV offshore medium-voltage grid up to a transmission level of 150 kV. The farm will be connected through a submarine 150 kV cable to land, and then – through the same corridor as the OWEZ – to the 150 kV grid close to the 380 kV Beverwijk substation (see Fig. 2). An overview of the main characteristics of the OWEZ and Q7 wind farms is presented in Table I.

Table I
Overview of Dutch Offshore Wind Farm Characteristics

	OWEZ	Q7
Distance from Shore (km)	10	23
No. Turbines	36	60
Turbine Power (MW)	3	2
Hub Height (m)	70	59
Capacity (MW)	108	120
Capacity Factor	0.37	0.42
Yearly Energy (GWh)	350	435
Equivalent No. Households	100000	125000

The 2007 onshore wind energy production from the 1620 MW installed was approximately 3500 GWh, or about 3% of the Dutch electricity demand, resulting in a capacity factor of 25%, understandably lower than the

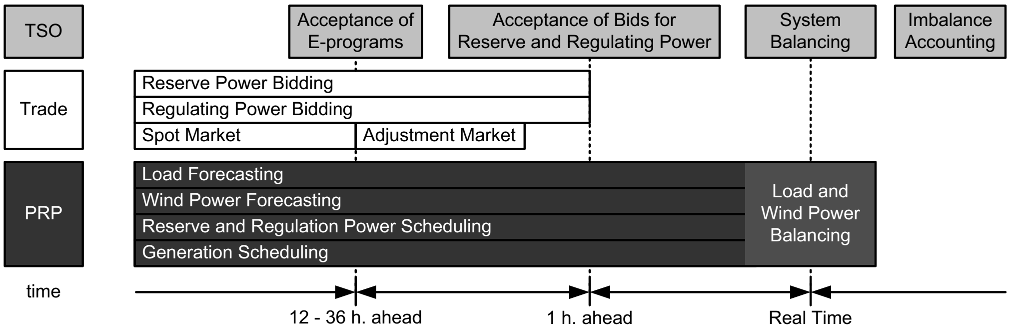

Figure 3. Activities and participants in the Dutch markets.

capacity factors quoted for the two offshore wind parks. The average onshore turbine size is now at 885 kW. However, the average installed capacity per turbine for *new* projects is somewhere between 2 and 3 MW, with the major players being Vestas and Enercon.

III. Structure of Dutch Markets

In the Netherlands, wind power is treated on an equal footing with conventional generation and is thus fully integrated in the day-ahead and imbalance market structures. The Dutch TSO TenneT is not responsible for operating wind power, nor for performing system-aggregated wind power forecasts, as is the case e.g. for system operators in the Danish or German control areas. Instead, wind producers sell their output to an energy company, or more likely enter into the various markets together with a mixed portfolio participant, that operates both conventional and renewable resources. These participants, recognized as Program Responsible Parties (PRP), submit to the TSO balanced schedules for energy delivered to and absorbed from the system during a 15-minute interval, or Program Time Unit (PTU). This arrangement provides some protection from the full exposure to imbalance charges for the wind producer, as conventional units in the PRP's portfolio may act to correct energy program deviations due to wind variability and unpredictability.

A wholesale day-ahead market is operated by the Amsterdam Power Exchange (APX), and is cleared over hourly intervals. In addition, an intra-day, hour-ahead energy market has been operated by APX since Sept. 2006. The imbalance market, closing one hour before real-time, is operated by the TSO, which acts as a single buyer. This market is cleared over quarter-hourly intervals, and the settlement rules make it a dual-imbalance pricing system, with payments based on the price of the marginal balancing bid called upon by the TSO during that PTU. A summary of the time-line and actors involved in the various markets in the Netherlands is shown in Fig. 3.

Under the *MEP* support mechanism (translated from Dutch as "Environmental Quality of Electricity Production"), in effect since 2003, renewable electricity generators in the Netherlands receive subsidies which depend on the difference in costs (including investment, operation and maintenance cost) between their facilities and conventional generation units. The maximum level of the subsidy is set at the difference between the production cost of offshore wind power and the average selling price of fossil-fuelled power. However, the subsidy does not apply to projects started after Aug. 2006, due to government concerns for over-reaching the target for electricity supply from renewable sources by 2010. A new support scheme is under discussion.

IV. Estimation of Balancing Requirements

In order to estimate the need for balancing power, both forecast errors and the variability of wind power production have to be investigated. In this work, the measured data originates from actually measured wind speeds at weather stations across the Netherlands and the North Sea, and the forecast data originates from real wind speed forecasts performed by the Energy Research Center of the Netherlands (ECN) using the the High Resolution Limited Area Model (HIRLAM). The data consists of one year time series of 15-minute averages for measured and forecasted wind speeds. The imbalance due to wind forecasting errors is conservatively estimated based on day-ahead predictions only, which means that the potential for more accurate hour-ahead predictions as applicable to intra-day markets is not considered.

An interpolation method that takes into account the spatial and temporal correlations among multiple sites, based on an exponential decay model for the covariance versus distance [9], is employed to derive time series of wind speeds and forecasts at the locations where wind farms are planned. The covariance data and the exponential decay fits are shown in Figs. 4 and 5, for wind speed measurements and wind speed forecast errors, respectively. Note that in Fig. 5 the data for wind speed forecast errors has been grouped by prediction lag, to account for the fact that forecasts at multiple sites become more highly correlated as the prediction horizon increases. A model similar to that in Fig. 4 has been constructed for the lag-1 (auto)covariances as well. We assume that the wind speed time series have the Markov property. This means that, given the measurements at time t, and the measured and interpolated values at time $t-1$, the interpolated values at time t are independent of values at previous time steps $t-k$, for $k>1$.

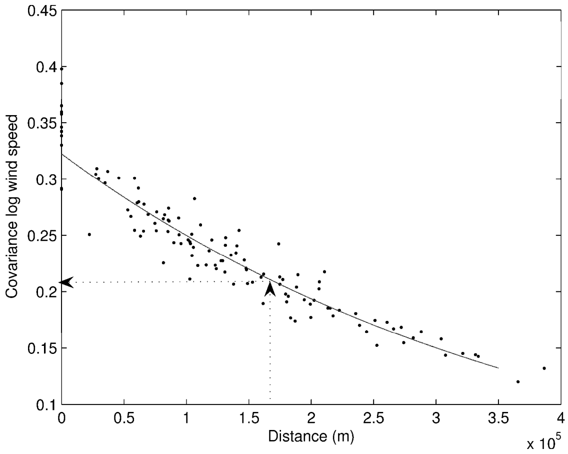

Figure 4. Wind speed covariance versus distance.

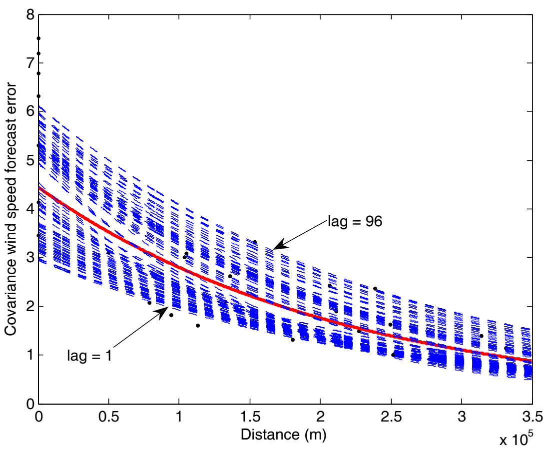

Figure 5. Wind speed forecast error covariance versus distance.

It was found that wind variability across consecutive 15-minute time intervals typically does not exceed plus/minus 12% of the system-wide installed wind capacity, while imbalances due to wind forecast errors could be as high as 50% (assuming a 24-36 hours prediction lag). Aggregating at the market participant level introduces slight inefficiencies, with a 2-3% increase in balancing energy requirements. This calculation was done assuming wind production is divided among 7 PRPs, with installed wind capacities in line with what we expect from the market players currently active in the Netherlands.

V. Integration Study using UC-ED

This section presents some results of a wind integration study performed by TSO TenneT in collaboration with Delft University of Technology, during 2006-2007, and published in [6] and [10]. Up to 8000 MW installed wind was simulated using a central unit commitment and economic dispatch (UC-ED) model. Wind capacity was divided up into 2000 MW installed onshore and 6000 MW offshore. The year 2012 was taken as a study case, with a foreseen composition of the conventional generation park as shown in Table II.

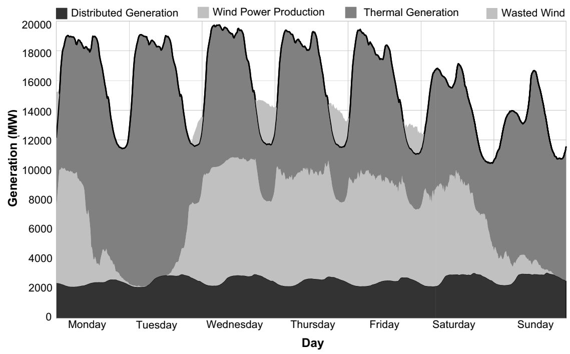

Figure 6. Weekly unit commitment and dispatch, 8 GW wind.

It was assumed that wind power does not replace conventional generation capacity. Wind power is curtailed as a last resort in case of constraint infeasibilities, such as conventional unit minimum output. Results are found to be sensitive to assumptions on the scheduling of imports, boiler capacities at CHP units, and unit flexibility (such as minimum up- and down-times). An example unit dispatch profile for a given week is shown in Fig. 6.

Available versus wasted wind energy over the simulated one year of operation is shown in Fig. 7, for various levels of installed wind power. System interchange was assumed to be zero to assess the technical capabilities of the Dutch conventional generation park itself. Obviously, flexible import schedules would provide additional technical space for integrating wind power. The output of distributed generation units was assumed to be 50% constant and 50% variable with system load, and entirely independent of the central dispatch. Wind power forecasts were updated hourly and used as an input into the UC-ED calculations. Minimum load problems appear around 4 GW installed wind power, as can be explained by the large percentage of heat-driven CHP units and non-dispatchable distributed generation (see Table II). In addition, it is found that due to the presence of must-run CHP units, large amounts of reserves are typically present in the Dutch system, providing sufficient regulating power to simultaneously balance the load and wind power variations.

VI. Storage

The study presented in the previous section was extended with models for three large-scale energy storage technologies: pumped hydro accumulation storage (PAC), underground PAC (UPAC) and compressed air energy storage (CAES) – with a capacity of 1500 MW.

Table II
Foreseen Dutch Installed Generation by 2012

Generation Type	GW	%
Gas-Fired	12.1	53
Coal-Fired	4.1	18
Nuclear	0.4	2
Other	1.3	4
Distributed Gen.	5.2	23
Total	22.9	100
of which CHP		55

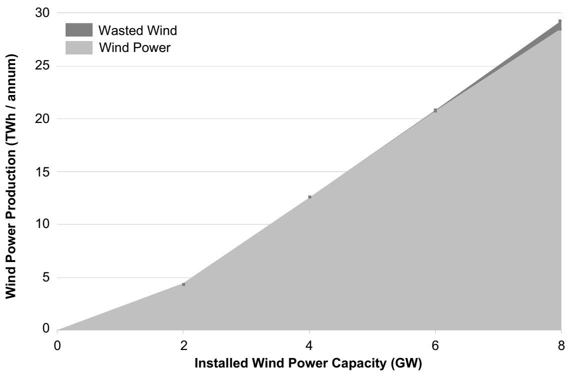

Figure 7. Available and wasted annual wind energy production.

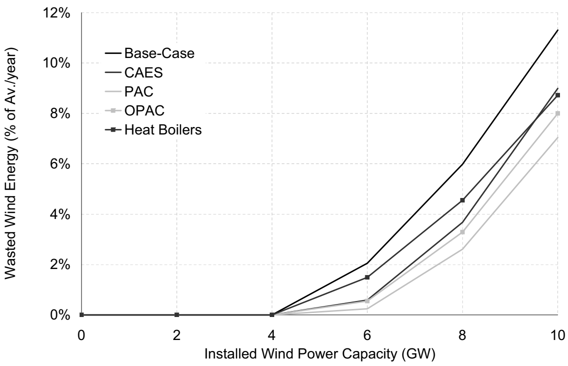

Figure 8. Curtailed wind due to minimum load problems.

Furthermore, an alternative solution was investigated, comprising the installation of heat boilers at selected combined heat and power locations (CHP) in order to increase operational flexibility of these units. For increasing installed wind power scenarios, results are shown for the base-case and for each storage solution, in terms of: wasted wind, cost savings and emissions in Figs. 8, 9 and 10 respectively.

As can be seen from Fig. 8, all options considered here indeed reduce the amount of wind wasted, i.e. that has to be curtailed, due to minimum-load problems. Energy storage and heat boilers all increase the flexibility of the Dutch system and thereby enable larger amounts of wind energy to be integrated, with PAC as the option with the highest potential for this. For the higher wind penetration levels, however, none of the options can separately prevent wasting wind energy altogether.

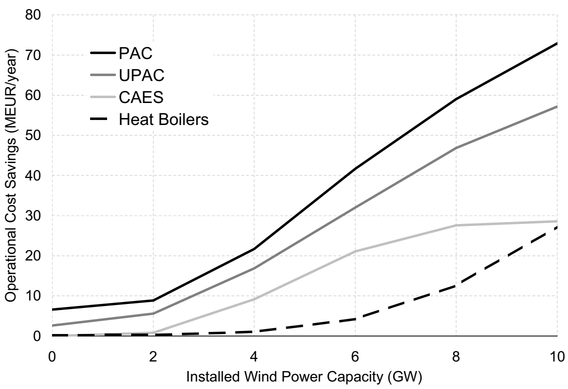

Figure 9. Operational cost savings compared to the base-case.

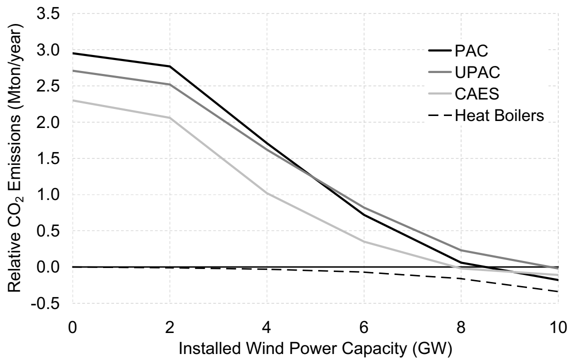

Figure 10. Relative CO_2 emissions for various storage alternatives compared to the base-case.

With the use of large-scale wind power, total system operating costs decrease – as shown in Fig. 9 and reported in [6] – due to the low operational costs of wind power. At the same time, wind power reduces the Dutch system's total CO_2 emission levels. Fig. 10 shows the emission levels of CO_2 compared to the base-case without energy storage or heat boilers. Interestingly, the simulation results show that the application of energy storage in the Dutch system increases overall CO_2 emissions.

The additional emission of CO_2 can be explained by two factors. For cost optimization, the storage reservoirs will be filled when prices are low, and emptied for generating electricity when prices are high. In the Dutch system, energy storage in fact substitutes peak-load gas-fired production by base-load coal-fired production. Since coal units emit more CO_2 on a MWh basis than gas units, the net coal-for-gas substitution by energy storage increases the overall amount of CO_2 emitted within the Dutch system. Secondly, energy storage brings about conversion losses which must be compensated by additional generation from thermal units, which again increases CO_2 emissions. From this, it follows that from a CO_2 emission perspective, energy storage is an option only for very high wind penetration levels, when energy storage prevents substantial amounts of wasted wind.

A cost-benefit analysis for the various storage options shows that the operation cost savings from energy storage increase with the amount of wind power installed. Taking into account the large investment costs, energy storage units are however unlikely to result in a profitable exploitation when the focus lies on optimizing the use of wind power. The installation of heat boilers at CHP-locations is found to be more efficient and a promising solution for the integration of large-scale wind power in the Netherlands [10].

VII. Conclusions

This paper presented an overview of the current status of implementation of onshore and offshore wind power in the Netherlands. After a description of the organization of the Dutch day-ahead, intra-day and imbalance markets, results of some system integration studies were summarized. High amounts of wind power may lead to constraint infeasibilities in the system starting around 4000 MW installed capacity. The paper showed the opportunities for energy storage and heat boilers to facilitate better integration of wind power in the Dutch system. However, from both an economic and an emissions perspective, it is unlikely that storage systems are the best solution. Adding more flexibility in the system and using (international) market mechanisms are more appropriate solutions as long as the share of wind power is moderate.

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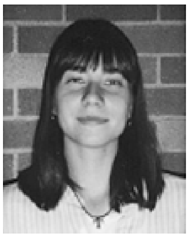
BIOGRAPHIES

Wil L. Kling received his M.Sc. degree in Electrical Engineering from the Technical University of Eindhoven in 1978. Since 1993 he has been a part-time Professor at the Delft University of Technology, in the field of Electrical Power Systems. In addition, he is with the Asset Management Department of the Dutch Transmission System Operator TenneT. Since 2000, he has also been a part-time Professor at the Technical University of Eindhoven. His area of interest is related to planning and operations of power systems. Prof. Kling is involved in scientific organizations such as CIGRE and the IEEE. As Netherlands’ representative, he is a member of CIGRE Study Committee C6, Distribution Systems and Dispersed Generation, and the Administrative Council of CIGRE.



Madeleine Gibescu received her Dipl.Eng. in Power Engineering from the University Politehnica, Bucharest, Romania in 1993 and her MSEE and Ph.D. degrees from the University of Washington in 1995 and 2003, respectively. She has worked as a Research Engineer for ClearSight Systems, and as a Power Systems Engineer for the AREVA T&D Corp. of Bellevue, Washington. She is currently an Assistant Professor with the Electrical Power Systems group at the Delft University of Technology, the Netherlands.

Bart C. Ummels received his M.Sc-degree in Systems Engineering, Policy and Management from Delft University of Technology, the Netherlands, in 2004. During his studies, he has done internships at Eltra, TSO of Western-Denmark (now Energinet.dk) and KEMA T&D Consulting, the Netherlands. Currently he is working towards a Ph.D. at the Power Systems Laboratory of Delft University of Technology. Furthermore, Mr. Ummels is involved in wind power integration studies at the Dutch TSO TenneT.

Ralph L. Hendriks received the B.Sc. and M.Sc. degrees in Electrical Engineering from Delft University of Technology in 2003 and 2005 respectively. Since 2005 he is a Ph.D. researcher at the High-Voltage Components and Power Systems section at Delft University of Technology, the Netherlands. His main research topic is grid integration of offshore wind farms through high-voltage direct-current transmission, with a special focus on synergies with interconnectors. From 2007 he is also a consultant with Siemens AG, Energy Sector, Erlangen, Germany. His research interests include power system stability and control, grid integration of large-scale renewable energy sources and modelling of power electronics.